

# High resolution radio observations of gamma-ray emitting Narrow-Line Seyfert 1s

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The detection by *Fermi*-LAT of  $\gamma$ -ray emission from radio-loud Narrow-Line Seyfert 1s (NLS1s) indicates that relativistic jets do not form only in blazars and radio galaxies, but also in other AGN populations. Despite a spectral energy distribution similar to blazars, their physical characteristics are quite different: lower black hole masses, generally higher accretion rates, and possibly hosted in spirals. Furthermore, their radio properties make the interpretation of these objects even more puzzling. The radio emission is very compact, not exceeding the parsec scales, as also found in the population of young radio sources. We present high resolution VLBA observations of three radio-loud NLS1s detected by *Fermi*-LAT: SBS 0846+513, PKS 1502+036, and PKS 2004–447. The information on the pc-scale morphology will be complemented with studies of flux density and spectral variability from multi-epoch and multifrequency observations, in order to unveil the nature of their radio emission.

## 1. Introduction

Narrow Line Seyfert 1 (NLS1) objects are a class of active galactic nuclei (AGN) discovered by Osterbrock & Pogge [1985] and identified by their optical properties: narrow permitted lines (FWHM ( $H\beta$ )  $< 2000 \text{ km s}^{-1}$ ) emitted from the broad line region,  $[OIII]/H\beta < 3$ , and a bump due to FeII (for a review see e.g. Pogge [2000]). They also exhibit high X-ray variability, steep X-ray spectra and a prominent soft X-ray excess. These characteristics point to systems with smaller masses of the central black hole ( $10^6$ – $10^8 M_\odot$ ) and higher accretion rates (up to 90% of the Eddington value) with respect to blazars and radio galaxies. Although NLS1s usually do not show strong radio emission, a small fraction ( $\sim 7\%$ ) is radio-loud [Komossa et al. 2006]. At radio frequencies, radio-loud NLS1s usually display a relatively compact morphology without extended structures, and strong and variable emission with a flat spectrum, suggesting that relativistic jets may form in these systems.

The discovery by *Fermi*-LAT of  $\gamma$ -ray emission in the radio-loud NLS1 PMN J0948+0022 [Abdo et al. 2009a] provided a strong support to the presence of a closely aligned relativistic jet. VLBI observations of PMN J0948+0022 pointed out the presence of a bright and compact component with an inverted spectrum that dominates the radio emission, and a faint jet feature [Doi et al. 2006, Foschini et al. 2011, Giroletti et al. 2011]. The variable emission and the brightness temperature exceeding the equipartition brightness temperature indicates that the source must be relativistically beamed, with Doppler factor  $\delta > 1$  [Giroletti et al. 2011].

Source	$z$	$\text{Log } L_{1.4\text{GHz}}$ (W/Hz)
PMN J0948+0022	0.585	26.19
1H 0323+342	0.061	24.73
PKS 1502+036	0.409	26.35
PKS 2004–447	0.24	26.11
SBS 0846+513	0.584	25.71

Table I Redshift and radio luminosity at 1.4 GHz for the gamma-ray NLS1s.

In addition to PMN J0948+0022, variable  $\gamma$ -ray emission was detected in other 4 NLS1 objects, all radio loud: 1H 0323+342, PKS 1502+036, PKS 2004–447 [Abdo et al. 2009b] and more recently SBS 0846+513 [Donato et al. 2011]. The increasing number of  $\gamma$ -ray detection of radio-loud NLS1s suggests that they form a new class of gamma-ray emitting AGNs. This discovery poses intriguing questions about our knowledge of the blazar sequence, the development of relativistic jets, and the evolution of radio-loud AGNs. Detailed studies of this new class of gamma-ray AGNs are fundamental for shedding light on the characteristics of these objects and the difference with respect to the other two AGN populations, blazars and radio galaxies, emitting in the gamma-ray energy band. Redshift and radio luminosity of the gamma-ray RL-NLS1s are reported in Table I.

Source	Array	Obs. date	Freq GHz	Flux mJy
SBS 0846+513	VLA	10 Apr 1986	5	286±11
	VLA	06 Jan 1996	5	332±13
	VLA	09 May 2009	5	196±8
	VLBA	06 Jan 1996	5	281±28
	VLBA	12 Mar 2011	8.4	210±21
PKS 1502+036	VLA	14 Apr 2007	22	611±24
	VLBA	11 Jan 2002	15	562±56
	VLBA	21 Jul 2006	15	545±54
PKS 2004-447	VLBA	13 Oct 1998	1.4	530±53

Table II Information on the datasets of the three RL-NLS1s discussed in this work, and their flux density.

## 2. Radio data

Among the 5 gamma-ray emitting NLS1s, we investigated the radio properties of the three objects lacking detailed studies of their radio emission: SBS 0846+513, PKS 1502+036, and PKS 2004-447. For this purpose we analysed archival VLA/VLBA data. When possible, we selected datasets at different epochs and at various frequencies in order to perform both variability and spectral studies. In Table II we report the information on the datasets considered in this work.

Radio data were retrieved from the archive and the data reduction was performed with the NRAO AIPS package. Images were produced in the standard way, after a few phase-only self-calibration iterations (a detailed discussion on the data analysis will be presented in a forthcoming paper).

In the following we present the main results on the radio properties of SBS 0846+513, PKS 1502+036, and PKS 2004-447 obtained from this analysis.

### 2.1. SBS 0846+513

SBS 0846+513 is the most recent NLS1 detected in gamma rays by *Fermi*-LAT [Donato et al. 2011]. Multi-epoch studies of the radio emission from the source indicate that the flux density has some degrees of variability (i.e. a variation of 70% at 4.8 GHz during 1986-2009). The resolution provided by the VLA is not adequate to resolve the source structure (Fig. 1). When imaged with the high spatial resolution provided by the VLBA, the source shows two asymmetric components resembling a core-jet structure (Figs. 2 and 3), as also pointed out in a previous work by Taylor et al. [2005]. The flux density ratio between components E and W is about 19 and 14 at 5 GHz and 8.4 GHz, respectively. They are separated by about 3.5 mas ( $\sim 23$  pc at source redshift  $z=0.5835$ ).

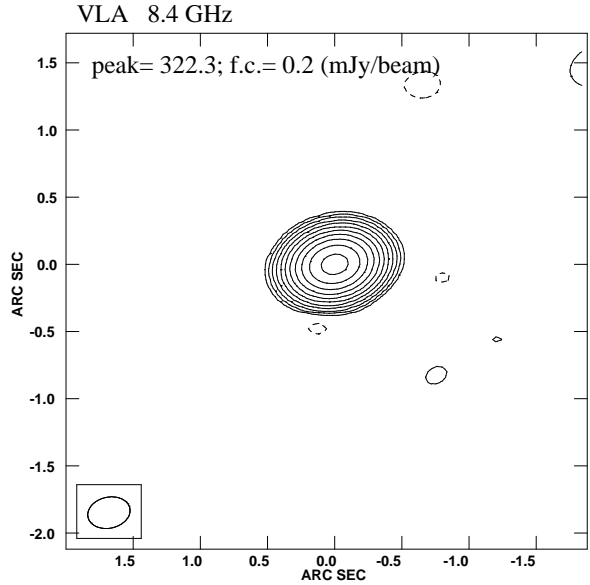


Figure 1: VLA image at 8.4 GHz of SBS 0846+513. On the image we provide the restoring beam, plotted in the bottom left corner, the peak flux density in mJy/beam, and the first contour (f.c.) intensity in mJy/beam, which is 3 times the off-source noise level. Contour levels increase by a factor of 2.

Although the source is unresolved with the VLA, pc-scale VLBA observations cannot recover all the VLA flux density. Such a discrepancy between the flux densities may be related to the intrinsic variability of the source. Even when VLA and VLBA observations were performed simultaneously (i.e. 1996, January 6), the VLBA flux density was only 85% of the value measured with the VLA at the same frequency. This suggests that the missing flux on parsec scale may be related to extended, low-brightness features, like a jet structure, that is resolved out by the VLBA array. For more details see D’Ammando et al. [2012].

### 2.2. PKS 1502+036

With its convex radio spectrum peaking above 5 GHz, PKS 1502+036 was selected by Dallacasa et al. [2000] as part of the bright sample of high frequency peakers (HFPs). Given the anticorrelation found between the intrinsic source size (i.e. age) and the spectral peak [O’Dea & Baum 1997], HFP objects should represent radio sources in the very earliest stages of their radio evolution. However, by the analysis of their radio properties (i.e. variability, morphology, polarization), it turned out that a great fraction ( $\sim 60\%$ ) of objects from the bright HFP sample are contaminant blazars rather than genuinely young radio sources [Orienti et al. 2008]. Based on simultaneous multifre-

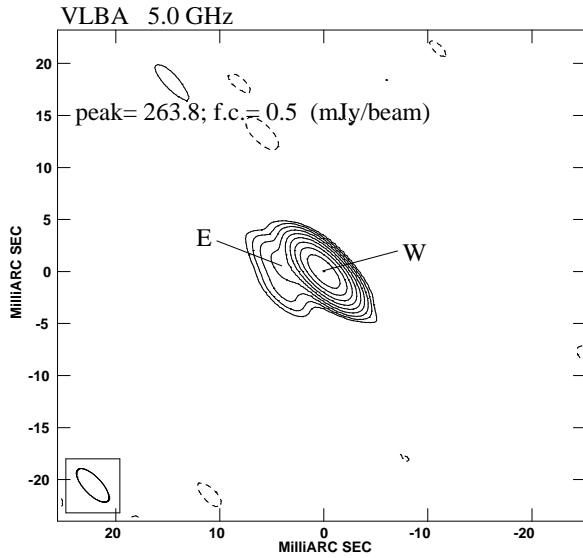


Figure 2: VLBA image at 5.0 GHz of SBS 0846+513. On the image we provide the restoring beam, plotted in the bottom left corner, the peak flux density in mJy/beam, and the first contour (f.c.) intensity in mJy/beam, which is 3 times the off-source noise level. Contour levels increase by a factor of 2.

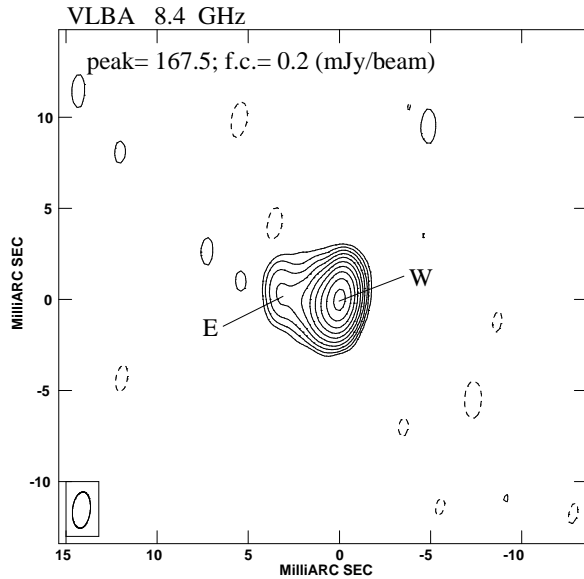


Figure 3: VLBA image at 8.4 GHz of SBS 0846+513. On the image we provide the restoring beam, plotted in the bottom left corner, the peak flux density in mJy/beam, and the first contour (f.c.) intensity in mJy/beam, which is 3 times the off-source noise level. Contour levels increase by a factor of 2.

### 2.3. PKS 2004–447

quency (from 1.4 to 22 GHz) VLA observations carried out in several epochs, PKS 1502+036 turned out to possess strong spectral and flux density variability (Fig. 4). During these epochs the spectral peak was at 7.6, 7.1, 6.4, 6.5, and 8.8 GHz, respectively. Variability is a typical property displayed by blazars, while young radio sources are non-variable objects. For this reason PKS 1502+036 was rejected from the HFP sample of young radio sources [Oriente et al. 2008]. PKS 1502+036 is unresolved on the typical VLA scales (Fig. 5). However, when imaged with the parsec scale resolution provided by VLBA observations, its radio structure is marginally resolved and a second component seems to emerge from the core. In the VLBA images at 15 GHz the double radio structure is clearly resolved suggesting a core-jet structure. The radio emission is dominated by the core component, while the jet-like feature is only 4% of the total flux density. Comparing the 15-GHz observations carried out at two different epochs (11 January 2002, and 21 July 2006, Figs. 6 and 7) it seems that in the second-epoch image there is a weak component of 4 mJy, separated by 3.05 mas ( $\sim 16.5$  pc at  $z=0.4088$ ) from the core which was not detected in the previous observations, although the sensitivity between the two observations is similar.

PKS 2004–447 is a powerful ( $L_{1.4\text{GHz}} \sim 1.3 \times 10^{26}$  W/Hz) radio source at redshift  $z=0.24$  and it is one of the four radio-loud NLS1 detected in gamma rays during the first year of *Fermi* operation [Abdo et al. 2009b]. However its classification is still uncertain. Oshlack et al. [2001] classified PKS 2004–447 as a genuine radio-loud NLS1 based on the optical definition. At radio wavelengths it is characterized by a steep ( $\alpha > 0.5$ ,  $S(\alpha) \propto \nu^{-\alpha}$ ) synchrotron spectrum at high frequency (above 8.4 GHz) and the absence of significant flux density variability. When imaged with arcsecond-resolution (e.g. ATCA) it is unresolved. Based on these characteristics Gallo et al. [2006] proposed this source as a genuine compact symmetric object (CSO). On the other hand, PKS 2004–447 has been included in the CRATES catalog of flat spectrum objects [Healey et al. 2007] due to its flatter spectrum ( $\alpha \sim 0.3$ ) below 4.8 GHz, questioning the nature of the radio emission. Indeed a flat spectrum is usually an indication of a self-absorbed component as in the blazar population, where the emission is dominated by the core region enhanced by projection effects. However, a flat spectrum may also be an indication of a convex spectrum as those found in young radio objects, whose spectral peak occurs between the frequencies considered.

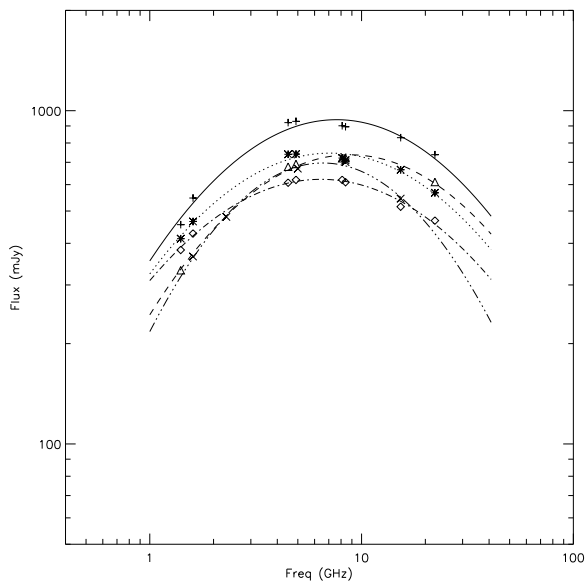


Figure 4: Multi-epoch radio spectra of PKS 1502+036 observed with VLA and VLBA during 5 observing runs: + and solid line = 25 September 1999 (VLA); asterisk and dot line = 03 July 2002 (VLA); diamonds and dot-dash line = 13 September 2003 (VLA); X and dash-3dots line = 21 July 2006 (VLBA); triangles and dashed line = 14 April 2007 (VLA). VLA data are from Dallacasa et al. [2000], Orienti et al. [2007], Tinti et al. [2005].

So far the only information on the pc-scale structure of PKS 2004–447 is from archival VLBA data at 1.4 GHz (Fig. 8). The radio structure has an angular size of 45 mas (170 pc) with a position angle of  $-50^\circ$ , and it is resolved into 3 main components. The lack of the spectral index information does not allow us to unambiguously classify the sub-components. For example the compact component A can be either the core of a core-jet boosted blazar, or a bright hotspot of an asymmetric young radio source.

### 3. Discussion and future work

Relativistic jets are the most extreme manifestation of the power generated by a super massive black hole (SMBH) in the center of an AGN, with a large fraction of this power being emitted in the gamma-ray energy band. Gamma-ray emission from radio-loud NLS1s provides evidence that relativistic jets may be not a peculiarity of blazars and radio galaxies/quasars, both hosted in giant elliptical galaxies. NLS1s are generally hosted in spiral galaxies [Deo et al. 2006, Zhou et al. 2006], and the presence of relativistic jets in these objects challenges the paradigm that the relativistic jets can form only in elliptical [Marscher 2009]. However,

only for one out of the five gamma-ray NLS1s, 1H0323+342, a high resolution HST observation suggests that this AGN is hosted in a spiral galaxy [Anton et al. 2008, Zhou et al. 2007]. Multi-band campaigns aimed at studying the Spectral Energy Distribution (SED) of this possible new gamma-ray emitting population pointed out that their physical properties and jet power are similar to those found in blazars. In particular the jet power estimated for PMN J0948+0022 and PKS 1502+036 is in the region of flat spectrum radio quasars (FSRQ), while in the case of 1H0323+342 and PKS 2004–447 the jet power is in the range typical of BL Lac objects [see Abdo et al. 2009b].

The blazar-like behaviour of these objects casts doubts questioning their nature and role in the context of the blazar sequence. Considering the relative small black hole masses and the high accretion rates, RL-NLS1s allow us to extend the physical properties of relativistic objects to low-mass systems. However, models developed so far can fit the SED only from the IR to shorter wavelengths, leaving the low-energy part of their spectrum not fully understood.

From the preliminary analysis of the radio data presented here, we found that all the sources are compact on kpc scales, but they are resolved on parsec scales. The radio emission of SBS 0846+513

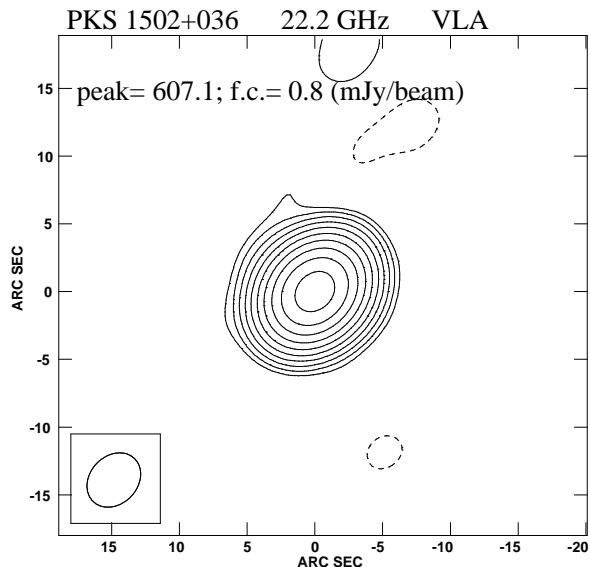


Figure 5: VLA image at 22.2 GHz of PKS 1502+036. On the image we provide the restoring beam, plotted in the bottom left corner, the peak flux density in mJy/beam, and the first contour (f.c.) intensity in mJy/beam, which is 3 times the off-source noise level. Contour levels increase by a factor of 2.

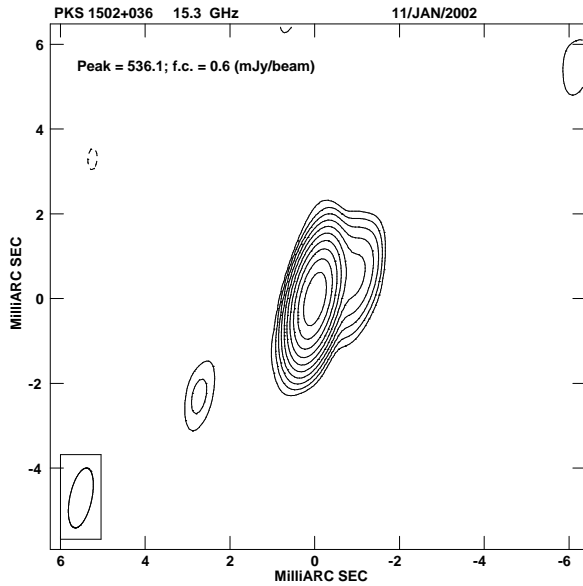


Figure 6: VLBA image at 15.3 GHz of PKS 1502+036 collected on 11 January 2002. On the image we provide the restoring beam, plotted in the bottom left corner, the peak flux density in mJy/beam, and the first contour (f.c.) intensity in mJy/beam, which is 3 times the off-source noise level. Contour levels increase by a factor of 2.

and PKS 1502+036 is dominated by a flat-spectrum compact and bright component from which a fainter jet-like feature emerges. Both sources show substantial flux density variability.

In the case of PKS 1502+036, the availability of two-epoch VLBA observations at 15 GHz allowed us to detect a new component at about 3 mas from the central region that was not visible in the first observing epoch. Assuming that this component is the same knot of the jet detected at about 1 mas during the first epoch, we estimate an apparent superluminal expansion velocity of  $\sim 8c$ , providing further evidence for boosting effects. However, with only two observations taken with a time separation of 4 years, we cannot unambiguously state that the two components are the same one at the different epochs. To confirm this result we are now analyzing additional archival VLBA observations which allow a better time sampling.

The interpretation of the radio properties of PKS 2004-447 is more uncertain due to the lack of spectral information. In fact, the bright and compact component at the easternmost edge of the source may be either the source core, or a very compact hot-spot like those found in a few young radio sources [e.g. Orienti et al. 2006]. The little flux density variability reported by Gallo et al. [2006], and its steep spectrum

above 8.4 GHz make PKS 2004-447 a candidate of being a young radio source rather than a blazar. To unveil the nature of this source new multifrequency observations with parsec-scale resolution have been requested.

Although the radio properties are important to constrain the emission mechanisms in the low-energy part of the spectrum of RL-NLS1s, at centimeter wavelengths, i.e. those discussed here, their emission is highly affected by synchrotron self-absorption. The one-zone homogeneous model adopted for the broad-band SED of these sources [e.g. Abdo et al. 2009b] is based on a single synchrotron emission component which does not fit the radio data, being all the emission below  $10^{12}$  Hz considered self-absorbed. Information on the mm/sub-mm emission is fundamental to set tight constraints on the low-energy emission, and ALMA observations will open a new window for investigating these sources in an unexplored frequency domain.

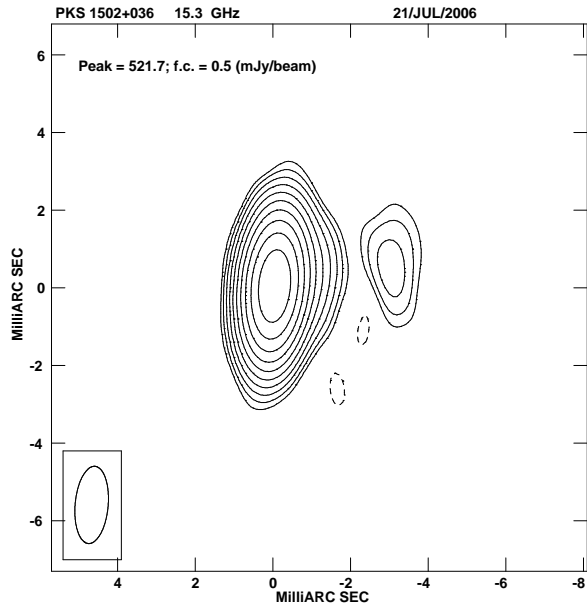


Figure 7: VLBA image at 15.3 GHz of PKS 1502+036 collected on 21 July 2006. On the image we provide the restoring beam, plotted in the bottom left corner, the peak flux density in mJy/beam, and the first contour (f.c.) intensity in mJy/beam, which is 3 times the off-source noise level. Contour levels increase by a factor of 2.

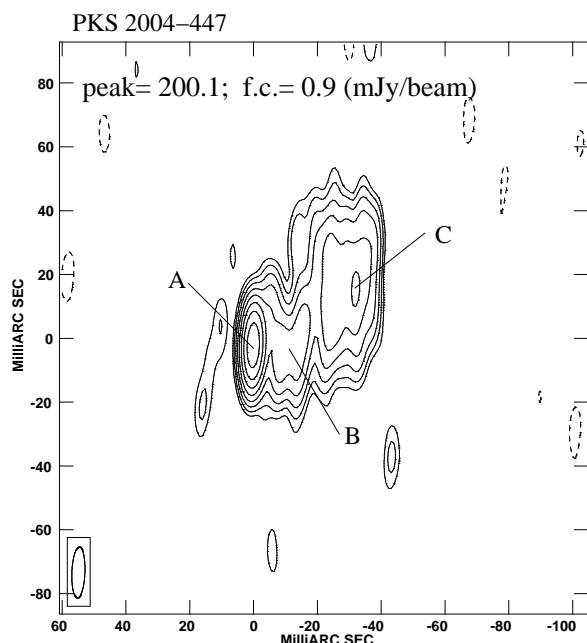


Figure 8: VLBA image at 1.4 GHz of PKS 2004-447. On the image we provide the restoring beam, plotted in the bottom left corner, the peak flux density in mJy/beam, and the first contour (f.c.) intensity in mJy/beam, which is 3 times the off-source noise level. Contour levels increase by a factor of 2.

## Acknowledgments

The *Fermi* LAT Collaboration acknowledges support from a number of agencies and institutes for both development and the operation of the LAT as well as scientific data analysis. These include NASA and DOE in the United States, CEA/Irfu and IN2P3/CNRS in France, ASI and INFN in Italy, MEXT, KEK, and JAXA in Japan, and the K. A. Wallenberg Foundation, the Swedish Research Council and the National Space Board in Sweden. Additional support from INAF in Italy and CNES

in France for science analysis during the operations phase is also gratefully acknowledged. The VLA and the VLBA are operated by the US National Radio Astronomy Observatory which is a facility of the National Science Foundation operated under cooperative agreement by Associated Universities, Inc. This research has made use of the NASA/IPAC Extragalactic Data base (NED) which is operated by the Jet Propulsion Laboratory, California Institute of Technology, under contract with the National Aeronautics and Space Administration.

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